Calibration of SCIAMACHY Using AATSR Top-of-Atmosphere Reflectance Over a Hurricane

Olivier Jourdan, Alexander A. Kokhanovsky, and John P. Burrows

***Abstract*—This letter investigates the synergy between the Scanning Imaging Absorption Spectrometer for Atmospheric Chartography (SCIAMACHY) and the Advanced Along Track Scanning Radiometer (AATSR) onboard the ENVISAT platform for reflectance calibration purposes. This calibration study was mainly performed over a portion of a hurricane corresponding to fully cloudy SCIAMACHY and AATSR pixels. Results show that SCIAMACHY underestimates the top-of-atmosphere (TOA) reflectance by up to 23% (at 870 nm) as compared to AATSR for a nadir viewing geometry. Specifically, considering AATSR calibration as accurate, which is confirmed by comparison with the Medium Resolution Imaging Spectrometer, the SCIAMACHY TOA reflectances should be multiplied by 1.21, 1.19, 1.23, and 1.10 for wavelengths at 550, 670, 870, and 1600 nm, respectively, ahead of satellite retrieval schemes based on the measurements of TOA reflectance.**

***Index Terms*—Advanced Along Track Scanning Radiometer (AATSR), calibration, Medium Resolution Imaging Spectrometer (MERIS), satellite instrumentation, Scanning Imaging Absorption Spectrometer for Atmospheric Chartography (SCIAMACHY).**

I. Introduction: Overview of SCIAMACHY Calibration Issue

THE Scanning Imaging Absorption Spectrometer for Atmospheric Chartography (SCIAMACHY) is a moderate-resolution imaging spectrometer [4] onboard ENVISAT. It is designed to measure the scattered and reflected spectral radiance in nadir and limb geometry, the spectral radiance transmitted through the atmosphere (solar and lunar occultation geometry), and the extraterrestrial solar irradiance and lunar radiance. It was launched on orbit on March 1, 2002. Measurements are expected to continue for at least another four years (until 2010). Data are recorded at moderate spectral resolution (0.2–1.5 nm) in a spectral range of 240–1750 nm divided in six channels as well as in two smaller spectral regions corresponding to 1940–2040 and 2265–2380 nm. In the nadir mode, the spatial resolution is between 30×30 and 30×240 km^2. Accordingly, SCIAMACHY's main objective is focused on the accurate measurements of trace gases in the terrestrial atmosphere. As most SCIAMACHY retrieval algorithms rely on studies of the depths of gaseous absorption bands of backscattered solar light [3], the accurate calibration of the instrument is not of primary importance. However, for the retrieval of the atmospheric optical thickness (OT) from space, accurate calibration is essential. Indeed, for optically thin atmospheric layers, radiative transfer calculations show that the OT is directly proportional to the top-of-atmosphere (TOA) reflectance. Therefore, calibration errors of, for example, 25% will produce in turn the same range of error for OT (for optically thin layers). The uncertainties in the forward model can increase the error even further or make the retrievals impossible (e.g., the aerosol TOA reflectance can become a negative number after removal of a well-defined molecular scattering contribution).

Numerous studies have been performed related to SCIAMACHY calibration, both reanalyzing ground data collected before launch of ENVISAT [11] and also using the comparison with the Medium Resolution Imaging Spectrometer (MERIS) TOA reflectances [1], [8], [14].

MERIS is a 68.5° field-of-view pushbroom imaging spectrometer that measures the solar radiation reflected by the Earth, at a ground spatial resolution of 300 m, in 15 spectral bands, programmable in width and position, in the visible and near infrared. MERIS allows global coverage of the Earth in three days. The reduced resolution mode (RRM) of MERIS has a spatial resolution of 1040 m across track and 1160 m along track. Measurements are performed in nadir geometry in 15 narrow channels with an average spectral width of 10 nm [2], [14].[1] Moreover, Delwart *et al.* [5] showed that the calibration error of MERIS was below 4%.

The analysis performed by several groups confirmed that TOA reflectances measured by SCIAMACHY are too low as compared to MERIS measurements. Previous works emphasized that SCIAMACHY calibration errors vary from 10% to 25% depending on the channel and the ground reflectance conditions (see, among others, [1], [6], [10], [11], and [14]). Although there are physical grounds behind the possible changes

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[1]More specifically, the channels are centered on the following wavelengths: 412.5 nm (10 nm), 442.5 nm (10 nm), 490 nm (10 nm), 510 nm (10 nm), 560 nm (10 nm), 620 nm (10 nm), 665 nm (10 nm), 681.3 nm (7.5 nm), 708.8 nm (10 nm), 753.8 nm (7.5 nm), 760.6 nm (3.8 nm), 778.8 nm (15 nm), 865 nm (20 nm), 885 nm (10 nm), and 900 nm (10 nm) where the width of the correspondent channel is given in brackets.

of the error with the wavelength (e.g., due to the spectral reflectance of films and coatings on the optics of an instrument), the calibration factors should not depend on surface reflection. However, comparisons between SCIAMACHY and MERIS measurements showed that significant differences of reflectances were encountered between these two instruments depending on the surface type. The biases were always found to be larger for underlying water surfaces. In particular, Acarreta and Stammes [1] found that the difference with MERIS was only 15% over land but 25% over ocean for the 885-nm wavelength. We believe that such an estimation of calibration error is more reliable over an ocean surface because the surface contribution is less important at 885 nm for ocean compared to that of land. It also should be pointed out that the bidirectional properties of the surface and its horizontal inhomogeneity may influence the main assumption of a vicarious calibration, i.e.,

$$\bar{R} = \int R(\vec{r})d\vec{r} \tag{1}$$

for sensors having significantly different spatial resolutions. In (1), $\bar{R}$ is the reflectance measured by a sensor having a coarse spatial resolution ($\sim$2000 km^2 in the case of SCIAMACHY), and $R(\vec{r})$ is the reflectance measured by an instrument with a high spatial resolution (e.g., $\sim$1 km^2 as in the case of MERIS) at the point characterized by the two-dimensional radius vector $\vec{r}$. Furthermore, the violation of (1) can be also due to discrepancies in observation angles of instruments under comparison. Under condition that (1) holds, results of Acarreta and Stammes [1] assert that the calibration factor indeed depends on the ground scene, being systematically smaller for bright surfaces (in the 442–885-nm wavelength range). On the other hand, as we mentioned above, due to the linearity of detectors, the bias between MERIS and SCIAMACHY calibration factors should not depend significantly of the scene studied. It points out that the relationship presented in (1) does not hold for all cases. Therefore, it is more adequate to perform a calibration study over a homogeneous surface or to use wavelengths where the surface contribution is low.

To address further the SCIAMACHY calibration issue, we have performed the vicarious calibration of SCIAMACHY over a hurricane with an underlying ocean surface, using yet another optical instrument on ENVISAT, namely the Advanced Along Track Scanning Radiometer (AATSR). This is considered in the next section.

II. Vicarious Calibration of SCIAMACHY Using AATSR TOA Reflectance

AATSR employs a dual view where each scene is viewed at nadir and at a forward angle of 55°. Its field of view covers a 512-km-wide curved swath centered at nadir, and the ground pixel size is 1×1 km^2 at the center of the nadir scan. The spectral information of the sensor is divided in three thermal infrared channels centered at 3.7, 11, and 12 μm and four visible/near-infrared channels (20 nm wide except for a 60-nm-wide channel centered at 1.6 μm) centered at 0.55, 0.67, 0.87, and 1.6 μm. According to SCIAMACHY spectral resolution, these four channels can directly be exploited for TOA reflectances comparison between SCIAMACHY and AATSR. Additionally, the calibration error of AATSR is small and comparable with that of MERIS. The differences in MERIS–AATSR TOA reflectances are close to +3% for wavelengths at 0.55 and 0.87 μm and below 1% at 0.665 μm [13].

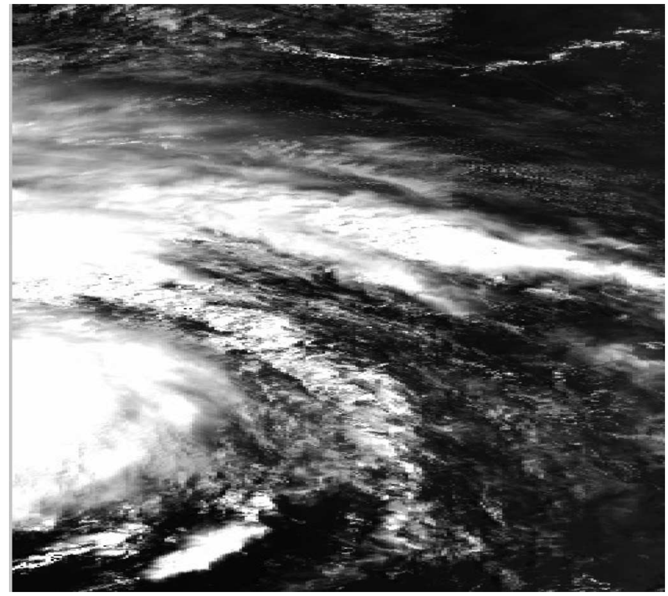

Fig. 1. Browse image of Hurricane Isabel as shown by AATSR.

Considering the calibration issues stated earlier, we chose to make a comparison of AATSR–SCIAMACHY reflectances over a scene with an underlying ocean surface that mainly encompasses optical thick cloud fields. In particular, this case study was conducted over Hurricane Isabel (orbit 08094 of ENVISAT, September 17, 2003, 14:50 UTC) with a center located at (72° W, 30° N) (Fig. 1). One can refer to our previous work [9] for further details on the selected scene. Level-1 (L1) SCIAMACHY products (version 5.0) were used in this letter.

The AATSR–SCIAMACHY reflectances intercomparison methodology follows the same procedure as the one proposed by Acarreta and Stammes [1]. First, the four visible/near-infrared AATSR channels (0.55, 0.67, 0.87, and 1.6 μm), which are within SCIAMACHY spectral range, were selected. Then, to compare L1 AATSR nadir products with L1 SCIAMACHY products, spectrally averaged nadir reflectances are calculated for SCIAMACHY at each AATSR visible/near-infrared spectral channel by integrating over the AATSR filter response function. The shape of the AATSR filter response function was chosen as a rectangular one. We believe that the choice of such a shape will not introduce significant errors compared to the real AATSR filter response function, as Acarreta and Stammes [1] found that the effect of the MERIS slit function was negligible on the change of the calibration factors. Additionally, the spectral dependence of the reflection function (RF) of cloudy scenes is negligible due to the large size of scatterers. The final step consisted in collocating 1×1 km^2 AATSR pixels within each set of 30×60 km^2 SCIAMACHY pixels on the basis of their longitude and latitude coordinates. Additionally, in this letter, only SCIAMACHY pixels corresponding to a cloud fraction

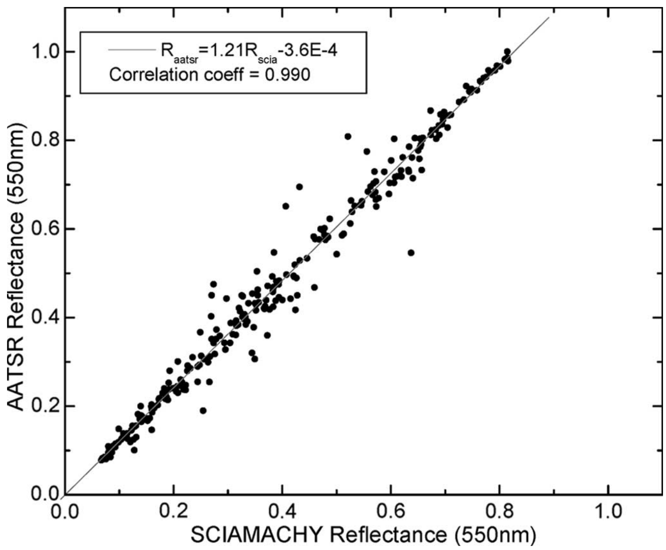

Fig. 2. Correlation between AATSR and SCIAMACHY reflectances at 550 nm.

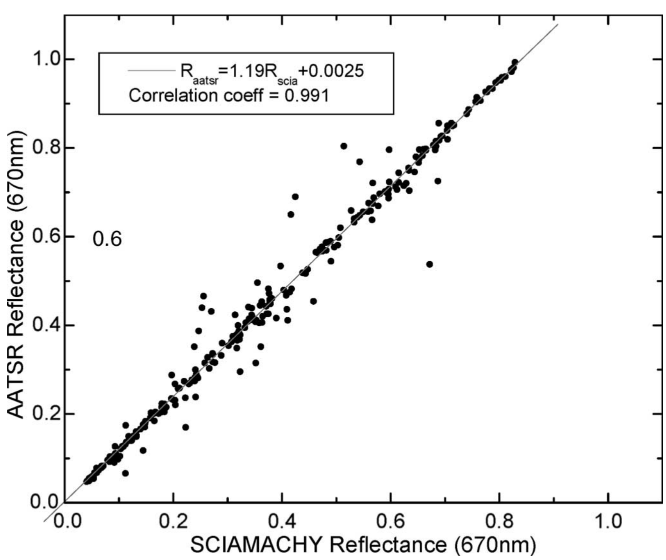

Fig. 3. Correlation between AATSR and SCIAMACHY reflectances at 670 nm.

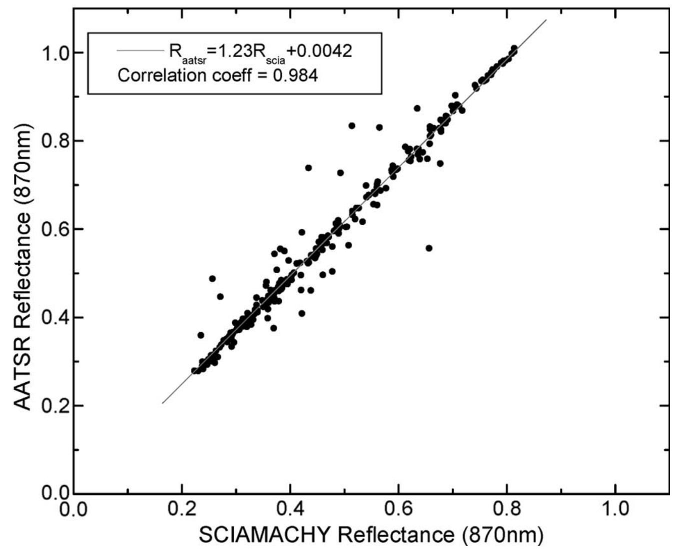

Fig. 4. Correlation between AATSR and SCIAMACHY reflectances at 870 nm.

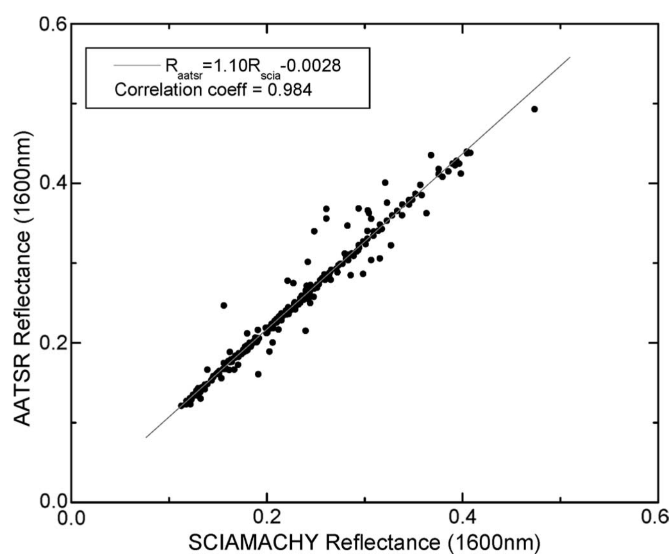

Fig. 5. Correlation between AATSR and SCIAMACHY reflectances at 1600 nm.

greater than 99% were selected. This pixel selection was based on a threshold technique of the SCIAMACHY and AATSR TOA reflectances at 0.87 μm. An AATSR pixel within a given SCIAMACHY pixel has been considered as completely cloudy if the RF at 0.87 μm of both instruments exceeded the threshold value of 0.2 [7]. In turn, the number of AATSR cloudy pixels within the SCIAMACHY pixel gives an estimation of the cloud cover of the SCIAMACHY pixel. The pixels fulfilling these criteria were used to investigate the possibility to establish linear relationships between SCIAMACHY and AATSR reflectances and, therefore, perform a calibration study.

We believe that a scene containing a hurricane structure is a good choice for the vicarious calibration of SCIAMACHY, not only because the levels of backscattered light intensity on SCIAMACHY detectors are quite large and variable but also due to the relative homogeneity of the spectral TOA RF. Additionally, the RF of the thick clouds under study is only slightly dependent on the observation angles and wavelengths. This reduces the possible influence of the observation geometry and the spectral instrument sensitivity function on the calibration coefficient. The possible effects of the surface inhomogeneity and the contribution from the lower troposphere are also significantly reduced in such targets.

The results of the AATSR–SCIAMACHY reflectances intercomparison are presented in terms of linear regression plots displayed for four wavelengths in Figs. 2–5. It follows from the analysis of Figs. 2–5 that AATSR reflectances (R_{aatsr}) and SCIAMACHY reflectances (R_{scia}) are almost perfectly correlated, with a correlation coefficient larger than 98%. The least square fit error is close to 0.01 for each wavelength, and the offset has a maximum value of 0.004, indicating that overall the fit is acceptable. However, R_{scia} are lower by 21% at 550 nm, 19% at 670 nm, 23% at 870 nm, and 10% at 1600 nm as compared to R_{aatsr}. This is close to the earlier MERIS-based

TABLE I
VALUES OF THE CALIBRATION COEFFICIENT C AVERAGED FOR DIFFERENT GROUND SCENES

λ, nm	C	Reference
442	1.13	Acarreta and Stammes (2005) (ocean:1.18)
443	1.12	Tilstra and Stammes (2006) (POLDER)
490	1.13	Tilstra and Stammes (2006) (POLDER)
510	1.13	Acarreta and Stammes (2005) (ocean:1.17)
550	1.21	this work
565	1.14	Tilstra and Stammes (2006) (POLDER)
665	1.15	Acarreta and Stammes (2005) (ocean:1.19)
670	1.19	this work
708	1.18	Acarreta and Stammes (2005) (ocean: 1.21)
765	1.16	Tilstra and Stammes (2006) (POLDER)
870	1.23	this work
885	1.21	Acarreta and Stammes (2005) (ocean:1.25)
910	1.21	Tilstra and Stammes (2006) (POLDER)
1600	1.10	this work

findings reported above. Moreover, the calibration coefficient $C = R_{\mathrm{aatsr}}/R_{\mathrm{scia}}$ at 870 nm is equal to 1.23, which is in close agreement with the value $C = 1.25$ reported by Acarreta and Stammes [1] at 885 nm for MERIS measurements over ocean. Results of vicarious calibration using AATSR compared to the one reported by Acarreta and Stammes [1] are presented in Table I. It ensues from this table that MERIS and AATSR give comparable calibration coefficients with respect to SCIAMACHY. We chose not to report the offset in our table because it represents a low reflectance value and can be neglected. This is confirmed by other independent calibration studies [1], [14]. Results for calibration coefficients obtained using the comparison of SCIAMACHY measurements with those of POLDER instrument (see http://smsc.cnes.fr/POLDER/ for the description of the instrument) have been presented by Tilstra and Stammes [13]. They are also given in Table I. The calibration coefficients found are consistent with previous findings reported by Acarreta and Stammes [1] obtained using MERIS.

It follows that C generally increases with the wavelength except for the case at 1600 nm, where the calibration error is at minimum $(C = 1.1)$. A similar trend is shown in the analysis of ground SCIAMACHY calibration data as reported by Noël [11][2] (dotted points in Fig. 6). This behavior was also found by von Hoyningen-Huene *et al.* [14], who determined, using MERIS observations, values of C equal to 1.10, 1.12, and 1.21 for SCIAMACHY channels 3 (394–620 nm), 4 (604–805 nm), and 5 (785–1050 nm), respectively.

Fig. 6 displays the spectral dependence of SCIAMACHY calibration factors obtained from measurements carried out at ground before launch of ENVISAT (open circles) and derived from MERIS (full black squares), AATSR (open triangles), and POLDER (stars) data. The calibration coefficients represented by open circles in Fig. 6 (except for highly oscillating results at the edge of SCIAMACHY channels) will be used in the next version of SCIAMACHY processor (version 6.0, S. Noël, private communication). In this way, after this recalibration is achieved, MERIS and SCIAMACHY will have very similar reflectances at 442 and 510 nm. The reflectance of SCIAMACHY for other wavelengths will also come closer

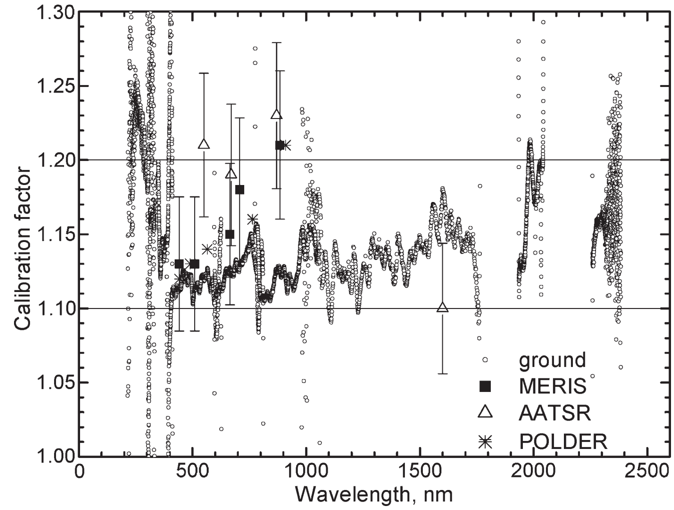

Fig. 6. Spectral dependence of the calibration factor measured at ground [11] and also using AATSR, MERIS, and POLDER. Bars show the estimated MERIS calibration error of 4% [5]. The difference in calibrations of MERIS and AATSR is smaller than 3% with the overestimation by AATSR [12].

to the results obtained by other instruments. However, except at 1600 nm, the SCIAMACHY reflectances will remain, on average, smaller than those of MERIS and AATSR.

In a previous work, Kerridge *et al.* [6] compared SCIAMACHY and AATSR reflectances for several heterogeneous ground scenes. In total, five scenes were analyzed, and both SCIAMACHY and AATSR reflectances were averaged over larger scenes of 480×512 km^2. They found calibration coefficients equal to 1.13 (at 550 nm), 1.10 (at 670 nm), and 1.19 (at 870 nm). The coefficient found at 870 nm is in agreement with the one reported by us and also to that obtained using MERIS (see Table I). The coefficients at smaller wavelengths are smaller than the ones we found but remain closer to those corresponding to average coefficients obtained from MERIS observations. This could be explained by the fact that coefficients reported by Kerridge *et al.* [6] and also by Acarreta and Stammes [1] correspond to highly heterogeneous scenes (e.g., water, vegetation, and clouds). Our results characterize a somehow more homogeneous scene encompassing a hurricane. However, our results remain comparable with MERIS observations over water surfaces. Yet, another possible reason of differences could come from the fact that previous AATSR–SCIAMACHY calibration studies were limited to scenes with lower reflectivity compared to the case studied in this letter.

Latter *et al.* [10] found that the calibration coefficients are 1.15 (at 550 nm), 1.05 (at 670 nm), 1.24 (at 870 nm), and 1.13 (at 1600 nm). They have also used AATSR for SCIAMACHY calibration based on the analysis of three complete orbits. However, instead of averaging AATSR pixels to the SCIAMACHY 30×60 km^2 scenes, much larger ground scenes were selected.

III. CONCLUSION

We confirm that the current version of SCIAMACHY processor (version 5.0) underestimates the TOA reflectance. The

[2]Refer to Fig. 6 and http://www.iup.physik.uni-bremen.de/sciamachy/SCIA_CAL/rad_cal.html for further details.

comparison of SCIAMACHY with AATSR measurements over a hurricane points out an underestimation of TOA reflectances by SCIAMACHY of 21%, 19%, 23%, and 10% at 550, 670, 870, and 1600 nm, respectively, which is generally consistent with the findings of Acarreta and Stammes [1] using MERIS. Kerridge *et al.* [6] used a similar approach as described in this letter and found calibration differences for SCIAMACHY around 13% (550 nm), 10% (670 nm), and 19% (870 nm) as compared to AATSR with a small variability depending on the scene studied. Latter *et al.* [10] reported the values of 15% (550 nm), 5% (670 nm), 24% (870 nm), and 13% (1600 nm) comparing AATSR and SCIAMACHY collocated measurements. The discrepancies of calibration constants reported by different authors could be due to the differences in the ground scenes and versions of processors used. Although there is a discrepancy with respect to the derived value of the SCIAMACHY calibration constants by different remote sensing groups, the underestimation of SCIAMACHY TOA reflectances can be considered as a well-established fact now. Therefore, we conclude that it is of importance to introduce the next version of SCIAMACHY processor as soon as possible to enable aerosol and cloud retrievals from SCIAMACHY measurements.

Clearly, because ENVISAT is planned to be in operation at least until 2010, more calibration efforts for SCIAMACHY will be needed in the future (e.g., using the moon as a light source for calibration). This new recalibration may remove small-scale oscillations present in the latest version of the calibration curve given in Fig. 6.

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